Energy 74 (2014) 164–173

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Laboratory investigation of hydraulic fracture networks in formations with continuous orthogonal fractures

Tie-gang Fan [a], Guang-qing Zhang [b,*]

[a] College of Mechanical and Transportation Engineering, China University of Petroleum, Beijing 102249, China
[b] College of Petroleum Engineering, China University of Petroleum, Beijing 102249, China

A R T I C L E I N F O

Article history:
Received 12 September 2013
Received in revised form
3 May 2014
Accepted 6 May 2014
Available online 11 June 2014

Keywords:
Hydraulic fracture network
Injection rate
Natural fracture density
Naturally fractured formation
Simulation experiment

A B S T R A C T

Researchers have recently realized that hydraulic fracture networks are significant for the exploitation of unconventional reservoirs (tight gas, shale gas, coalbed methane, etc.). Studies have shown that slick-water fracturing treatments can create complex fractures that increase the 'stimulated reservoir volume' in naturally fractured formations. However, the influence of the created hydraulic fracture network is not well understood. Laboratory experiments are proposed to study the evolution of hydraulic fracture networks in naturally fractured formations with specimens that contain two groups of orthogonal cemented fractures. The influence of dominating factors was studied and analyzed, with an emphasis on natural fracture density and injection rate. We concluded that hydraulic fracture networks are formed by the interactive process between the reopening and connecting of the natural fractures through slick-water fracturing in the specimens, indicated by frequent pressure fluctuations. The spatial envelope of the fracture network is an approximate ellipsoid with the major axis deviating from the orientation of the maximum horizontal stress. It is suggested from the pressure curve that great natural fracture density and high injection rates tend to raise the treatment pressure and the pressure profiles could reflect different characteristics of extending behaviors.

1. Introduction

Hydraulic fracture propagation in the presence of natural fractures is substantially different from those in reservoirs without natural fractures, as hydraulic fractures can have complex growth patterns in formations with systems of natural fractures that lead to significant diversion of hydraulic fracture paths due to intersections with natural fractures.

The problem of hydraulic and natural fracture interaction has been widely investigated both experimentally [1–5] and numerically [6–12]. These studies have suggested that the horizontal differential stress, the angle of approach and the treatment pressure affect hydraulic and natural fracture interaction [2–4]. In general, there are four types of interactions between a fluid-driven fracture and a natural fracture. Hydraulic fractures can cross the natural fracture directly, without any division of the fracture path. In the opposite extreme case, the hydraulic fracture may be arrested at the natural discontinuities by opening the joint or by a large slip along the contact. Between these two extremes, the hydraulic fractures and the fluid flow may potentially reach an intermediate state by being deflected into the natural fracture to form two branches. In some cases, the fracture turns into the natural fracture for a short distance and then breaks out again to propagate in a mechanically more favorable direction, depending primarily on the orientation of the natural fracture relative to the stress field [1,2,13–15]. Many field experiments have also demonstrated that a propagating hydraulic fracture encountering natural fractures may lead to the arrest of fracture propagation, fluid flow into natural fractures, creation of multiple fractures and fracture offsets [16–19], which will result in a reduced fracture width.

Early studies focused on the effect of a single natural fracture on the propagation of an induced hydraulic fracture, and some authors [3,20,21] have proposed fracture interaction criteria. Considering the formation of natural fractures, some studies have investigated the effect of discontinuities on hydraulic fracture propagation in multi-fractured mediums. De Pater and Beugelsdijk [22] used Portland cement model blocks in which there were random fractures formed by the heating process to investigate the effect of the

* Corresponding author. Room 802, North Wing, ZhongYou Building, China University of Petroleum, College of Petroleum Engineering, Changping, Beijing 102249, China. Tel.: +86 13 701353475; fax: +86 10 89733920.
E-mail addresses: zhang200800@gmail.com, zhangguangqing@cup.edu.cn (G.-q. Zhang).

http://dx.doi.org/10.1016/j.energy.2014.05.037
0360-5442/

injection rate on fracture propagation. The test results showed that a high flow rate or viscosity yields fluid-driven fractures, while a low flow rate just opens an existing fracture network. Zhou and Xue [23] also performed a series of experiments on Portland cement blocks to investigate the influence of random natural fracture systems and in-situ stress contrasts on the geometry and propagation behaviors of hydraulic fractures. Three types of geometries were observed in their tests: a vertical dominating fracture with multiple branches, which was created at high differences of horizontal stress; radial net-fractures around a wellbore at low differences of horizontal stress; and a partly vertical fracture (one wing) with random branches. Natural fractures prepared in this way, however, are not easily controlled, which results in too much uncertainty when investigating the effects of certain factors on hydraulic fractures, as specimens differ for each case. In this study, we propose a new method for specimen preparation, with well-controlled parameters for the specimens, in terms of the natural fracture distribution and bond condition. Olson et al. [24] embedded planar glass discontinuities into a cast hydrostone block as proxies for cemented natural fractures and used these blocks to perform tests to examine the effects of cemented natural fractures on hydraulic fracture propagation. Their results show that obliquely embedded fractures are more likely to divert a fluid-driven hydraulic fracture than those occurring orthogonally to the induced fracture path. Hydraulic fracture–natural fracture interaction took three forms: 1) the hydraulic fracture bypassing the natural fracture by propagating around it (via height growth, not curving), 2) the hydraulic fracture arresting into the natural fracture and then diverting along it and sometimes kinking off at the end of it, and 3) a combination of bypass and diversion.

Laboratory experiments are a common and practical way to investigate the physics of hydraulic fracture complexity, with the advantage of better boundary condition controls and near complete observation of fracture geometry. In the experimental design, specimen selection is very important. The formations to be hydraulically fractured are usually thousands of meters deep; appropriate retrieval of the drilling core is sometimes impossible and very costly. Limited by drilling technology, the size of the core may be too small to meet the dimensional requirements of the experiment. Therefore, artificial specimens become practical and indispensable. Most previous simulations have been performed on homogeneous and continuous blocks, without considering the discontinuity of features such as natural fractures, faults and planes of weakness. However, natural fractures are virtually always present in all rock formations, so there is an integral demand for an innovative specimen preparation method. Many researchers [4,22–24] have proposed various methods of preparing natural fractures in specimens for hydraulic fracturing, but in these methods, it is not easy to control the properties of the natural fractures, so some uncertainty must be factored into the experiment. Natural fractures caused by brittle failures remain initially open, but may be subsequently altered or mineralized; different types of fractures with different geometric and mechanical properties are found in the earth's crust. In this study, we proposed a method for specimen preparation. With this method, we can generate any number of natural fractures with arbitrary geometries in model blocks; the fractures form a complicated fracture network, and the characteristic parameters of the natural fracture system can be strictly controlled. This method can provide specimens that simulate the characteristics of natural fractures in formations for hydraulic fracturing experiments, making the experimental conditions considerably more consistent with in-situ situations.

Our goal was to investigate the effect of natural fractures on hydraulic fractures in naturally fractured formations with specimens containing two groups of orthogonal cemented or healed fractures. Normally fractures never occur alone, but as a series of subparallel fractures, or a joint set. Methods for characterizing the spacing, density, and trace lengths of fractures in sets were described by La Pointe and Hudson [25]. Although there are many varieties of fracture patterns in nature, types of fracture intersection geometries are relatively rare. Following Lachenbruch [26], fracture intersection geometries can be classified as orthogonal or non-orthogonal. Both types can be divided into three groups according to the continuity of the fractures at the intersections: all continuous fractures; some continuous and some discontinuous sets; and all discontinuous. In this study, a series of cuboid cement blocks of various sizes was produced to simulate the matrix, and cement pastes were used to bond the cement blocks to mimic "mineralized" or healed natural fractures. This research was motivated by observations in formations where most natural fractures are observed to be filled with calcite or quartz cements [27]. These cement pastes are analogous to natural fractures that are joined with a cement that is weaker than the surrounding host rock. We injected dyed water into the block under a true tri-axial stress state. The results show the influence of natural fracture density and injection rate on the fracture propagation behaviors.

2. Experimental setup and procedures

2.1. Experimental equipment

The hydraulic fracturing experiments reported here were conducted using a true tri-axial hydraulic fracturing test system (Fig. 1).

All of the external stresses are supplied using a hydraulic voltage stabilizer, and the injection pressure is supplied using a servo-controlled hydraulic pump MTS (Mechanical Testing & Simulation) 816. The system is capable of supplying external stresses of up to 28 MPa and injection pressures of up to 140 MPa to a 300 mm cubic specimen. The injection system is capable of pumping fluids with any injection scheme for continuous volumes up to 800 ml. The experimental control and data acquisition are conducted using customized software running on a PC (Personal Computer). This system has been used successfully to initiate and propagate hydraulic fractures in a variety of materials using different fracturing fluids.

2.2. Specimen preparation and experiment outline

The experiments described here were performed on six cubic specimens of 300 mm in lateral, prepared with a mixture of cement and 20–40 mesh natural siliceous sand with a constant mass ratio of 1:1. A series of various-sized cuboid blocks were made with the mixture material. The scheme is shown in Table 1. In this paper we defined the cuboid blocks as 'block units', and a certain amount of block units that had the same geometries compose a 'set'.

To simulate healed natural fractures, the block units in one set are cemented one by one using cement paste to form a 'big cuboid block'. For the natural fractures that remain open, we did not need to cement the block units. We simply arranged them according to the design pattern. In this study, we investigated the healed natural fractures, so all of the block units were cemented using cement paste. The 'big cuboid block' was then placed in the center of a metal mold with an inner space measuring 300 mm × 300 mm × 300 mm, and the same cement mixture was filled around it. The cement paste between the block units can be regarded as two groups of continuous cemented fractures, orthogonal to each other in the central part of the specimens. A schematic of the fracture system is shown in Fig. 2.

The specimens were allowed to cure for four weeks, at room temperature and humidity conditions, before a vertical borehole of 10 mm in diameter was drilled 160 mm deep and parallel to the